Visual Analysis of Wind Turbines in Denmark

F. J. Lamp, J. B. Møller, E. B. Sørensen, G. Walsh, J. Kusnick and S. Jänicke

Centre for Visual Data Science, Department of Mathematics and Computer Science, University of Southern Denmark, Odense, Denmark

Figure 1: *Overview of the Danish Wind Power Analytics Tool (DWPAT) which supports **(a)** geospatial analysis of wind turbines, (**b**) pairwise wind turbine comparison, (**c**) rotor size vs. capacity comparison, (**d**) analysis of market share by manufacturer, and (**e**) temporal analysis of energy production by energy source. A diversity of analysis tasks are supported through (**f**) dynamic filters and alternative geospatial views highlighting wind turbine (**g**) capacity and (**h**) count per municipality.*

Abstract

To adequately prepare for Denmark's future green transition of the energy market, analysts require sophisticated tools to explore the historical development and current state of the power infrastructure, in particular the wind power network, which has become Denmark's most important energy source. Such analyses require identifying and assessing the performance of wind turbines in terms of size, age, location, and manufacturer for replacement, repair, and extension purposes. Visualization tools performing such trend analyses of wind turbines according to these parameters are scarce. Addressing this shortcoming, we present the Danish Wind Power Analytics Tool (DWPAT). It uses data from the Danish Energy Agency to offer interactive visual representations of the geospatial distribution of wind turbines in Denmark based on various criteria such as manufacturer, municipality, and installation type. DWPAT provides comprehensive insights into wind energy production and enables direct comparisons between specific wind turbines and numerous other analytical characteristics to support the decision-making process of stakeholders in industry, federal and state governments, and research.

1. Introduction

Over the last decade, the energy transition from fossil fuels to renewable energy sources has been a major political topic due to climate change and, as a result of war conflicts, energy security [IEA22]. The European Wind Energy Association expects that 50% of Europe's electricity demand will be sourced from wind energy by 2050, contributing to the European Union's goal to cut greenhouse gas emissions [A*11]. In Denmark, wind energy accounts for a large share of total renewable energy production. In 2022, wind energy accounted for over 50% of Denmark's total energy production, generated by a fleet of more than 6,000 active wind turbines [Ene23]. However, obtaining a meaningful and in-

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formative overview is becoming increasingly challenging for domain experts and policy-makers as the wind energy infrastructure is continuously expanding [GBJM*21]. Major issues include finding appropriate spots for new wind parks, choosing high-performing wind turbines for selected locations, and fitting installation types and sizes. For such tasks, which are currently not sufficiently supported [BSBPL19], domain experts and stakeholders in the energy sector require sophisticated, intuitive interfaces to make well-informed and data-driven decisions. In particular, comparing the capacity and performance of individual wind turbines (of different types or of the same types at different locations) reveals useful insights, and it can further aid in locating low-performing turbines for maintenance purposes [RVL*21].

To address these needs, we conducted a participatory visual design approach [JKKS20] in close collaboration with domain experts from the wind power industry in developing the Danish Wind Power Analytics Tool (DWPAT) to establish a solid base for analyzing the contemporary state of Denmark's wind power market and help in decision making for energy planning, installations, maintenance and future developments of the wind turbine fleet. Target users include analysts from the energy sector and municipalities that want to develop strategies to expand their wind turbine infrastructure. DWPAT enables exploring the wind turbine distribution on different geospatial zoom levels, searching for and looking up individual turbines with particular features, comparing turbine data, and identifying trends with regard to infrastructure and capacity development.

2. Related Work

To intuitively visualize multivariate information such as the wind turbine database, domain experts require a comprehensive overview alongside the ability to filter and explore features in interlinked visualizations [WBWK00], very often implemented to depict correlations between temporal and geospatial data [AA06]. This approach has been successfully applied to develop diverse visual analytics tools, proven to ease the understanding of complex topics [VDK*13, KLLL23]. To support the development of effective solutions, domain-specific advancements are crucial for addressing unique data visualization challenges. An example is *HomeSeeker* [LBS*18], which visualizes local real estate markets for users at different expertise levels. The proposed visual analytics system offers multiple interactive views enabling tailored searches, pattern discovery, and detailed property comparisons, effectively linking geographical data to property prices utilizing choropleth and glyph maps. A similar approach is implemented in the Danish Companies Dashboard [HMN*22]. It supports the visual analysis of Danish companies on different geospatial levels of detail, which has provided inspiration for our work.

Visual Analysis of Wind Power. Only a few solutions exist to analyze wind turbine data. The USGA Energy Resources Program developed an analytics tool based on the United States Wind Turbine Database(USWTDB) [USG22]. It provides the locations of both onshore and offshore wind turbines in the United States [HDR*18]. While sophisticated in the use of glyph and heat maps for analyzing the geospatial distribution, it lacks comparative features and does not give insights into temporal development and performance. Aimed to aid policy-makers, planners, and investors in identifying global, national, regional, and local high-wind areas for potential new wind power generation, the Global Wind Atlas [BDD*24] illustrates occurring winds through a worldwide heatmap and accompanies that by further temporal and periodical analysis through line and radar charts. Contrary to expectations, existing wind turbine data is not included. For Denmark, one of the leading countries in the renewable energy sector, multiple map-based solutions already exist. A public digital register supports spatial planning in Denmark by providing manifold spatial information about renewable energy sources [IRE24], including solar power, and the spatial distribution of active wind turbines and their capacity can be explored [ENS24]. A similar map visualization aims to provide statistics to support renewable energy-oriented policy scenarios and communicate unique geospatial-temporal information to project developers, such as the environmental footprint throughout the life cycle of the turbines [BSBPL19].

Existing tools that support the analysis of the wind power market mainly focus on geospatial data of wind turbine data, but the temporal dimension is only marginally taken into account and complex comparative analyses are not supported. The purpose of the Danish Wind Power Analytics Tool (DWPAT) is to fill this gap.

3. Project Overview

The development of the Danish wind power analysis tool followed an iterative, participatory visualization design approach [JKKS20] with domain expert feedback loops throughout the development process. Our presented solution received input from industry through one of the co-authors, who worked for and developed DWPAT for Vestas Wind Systems [VES24], one of the world market leaders in wind turbines. On the other side, we included the research perspective by collaborating with the Center for Energy Informatics at the University of Southern Denmark [CEI24]. The domain experts pointed us to current limitations, such as the comparison of wind turbines and the lack of interlinked views, which led to the foundation of our project addressing needs regarding the analysis of Denmark's wind energy landscape on different scales. We identified the following requirements **(R1-R5)**:

- **Geospatial Analysis (R1)**: Experts must be enabled to explore wind turbine data aggregated at various semantic zoom levels.
- **Temporal Development (R2)**: The development and growth of electricity production from wind turbines must be put in context.
- **Performance and Size Analysis (R3)**: Wind turbines of interest must be selectable to support comparing their performance and size.
- **Contextual Information (R4)**: Experts wish to explore wind turbine data with additional features visualized (i.e., manufacturers, energy market).
- **Multifaceted Analysis (R5)**: Experts have different aims to using DWPAT, and thus require different modes of aggregation and filtering (by count, capacity, manufacturer, locations, municipalities, installation type, and time).

3.1. Data

Our incorporated data is collected from the nationwide wind turbine database from the Danish Energy Agency [DEA24] and Energinet [Ene24a]. The database is currently limited to static information from 2000-2022, but will in the future provide access to live data. The data set features 6,296 records of all active and decommissioned Danish wind turbines with capacities over 6 kW, detailing 59 attributes, which are categorized as categorical (e.g. manufacturer, model, installation type, municipality) or quantitative and sequentially ordered (e.g. capacity, rotor diameter, hub height, coordinates). Transformations for visualization include binning electricity production, turbine count, and capacity data into defined regions represented by Danish municipalities as well as the conversion of measurements and formats. To provide a better understanding of the role of wind energy in Denmark relative to other energy sources, a further data set from the Danish Energy Agency has been included [Ene24b], containing information about the total electricity production in Denmark for each month from 2000 to 2022 grouped by source of electricity generation.

4. Visual Design

DWPAT offers several views that support the interactive visual analysis of wind turbine data. Our implementation follows the Visual Information Seeking Mantra [Shn96], starting with a geospatial *overview*, then offering users *zoom and filter* functionality to navigate and focus on specific municipalities, wind turbine types, or manufacturers. Finally, users can obtain specific information about individual wind turbines and compare their *details on-demand*. A screenshot of DWPAT is given in Figure 1(a-f). It shows a navigation bar at the top, allowing analysts to choose among three map views. Additional filters from drop-down menus (Figure 1f) can be applied to select between off- and onshore wind turbines and to choose different manufacturers, which updates all views of DWPAT (**R5**). In the following, we describe their features, relation to requirements, and intended use with Munzner's *What*, *Why* and *How* questions for effective visual design [Mun14].

DWPAT features map views with different levels of geographical detail (**R1**), displaying the geospatial information of all active wind turbines in Denmark as of 2022.

Municipality View: This view illustrates the installed wind power capacity on a municipality level.

- *What:* It groups wind turbines by the municipality based on the actual geographical coordinates and determines values for the count and aggregate capacity.
- *Why:* This map allows for comparative analysis of municipalities to be used to filter wind turbines by administrative regions.
- *How:* A choropleth map is used to color Danish municipalities using two single hue color scales for capacity (green, Figure 1g) and turbine count (red, Figure 1h).
- *Use:* Analysts can spot particular municipalities and assess and compare their energy capacities and turbine counts. Guiding information on a municipality's wind turbines can be gathered through the Wind Production and Age Distribution Views. Selected municipalities can be explored in detail by switching to the Wind Turbine Distribution View.

Wind Turbine Distribution View: This view shows the exact locations of wind turbines and grants access to detailed information.

- *What:* It uses the actual geographical coordinates of wind turbine data, including physical dimensions and operational metrics.
- *Why:* This map allows for intricate analysis at the turbine level, essential for precise planning and maintenance strategies.
- *How:* A glyph map is used (Figure 1a) in which each turbine is represented as a dot colored on a yellow to green color scale reflecting turbine capacity. Hovering shows turbine feature data in a popup window, facilitating detailed exploration and understanding of wind energy infrastructure.
- *Use:* Analysts can compare arbitrary wind turbines with each other. For example, they can select two onshore wind turbines from different wind parks to compare their features using the Size Comparison and Rotor Size vs. Capacity Views.

Size Comparison View: We designed a wind turbine chart to illustrate the spatial dimensions of selected turbines visually (**R3**).

- *What:* It uses wind turbines' rotor diameter and hub height.
- *Why:* This view supports comparing physical attributes and understanding the relationship between rotor size and energy capacity, the key to turbine performance.
- *How:* This view will illustrate up to two wind turbines selected in either the Wind Turbine Distribution View or the Rotor Size vs. Capacity View. Icons reflecting turbines are designed to compare turbine parts, such as the tower and rotor, using a green color scale to indicate capacity (Figure 1b).
- *Use:* Analysts can evaluate turbine suitability for different locations based on environmental and spatial constraints, assessing environmental impact and operational efficiency. In addition, they can choose to filter by manufacturer and turbine model for a more detailed analysis.

Rotor Size vs. Capacity View: This view supports analyzing the relationship between rotor size and capacity.

- *What:* It uses rotor diameter, capacity, and benchmark data for wind turbines [GLA16].
- *Why:* This view allows analysts to compare turbine attributes and identify performance outliers, assisting in turbine selection by bench-marking against expected efficiency and design metrics.
- *How:* The correlation between rotor diameter and capacity is shown in a scatter plot illustrating size-performance relationships; benchmarks are blue curves.
- *Use:* Analysts can easily spot under and over-performing turbines and compare different turbine models through synchronous highlighting with the Size Comparison View.

Age Distribution View: For a selected municipality, a histogram allows analysts to investigate the age distribution of wind turbines (**R2**), summarizing ages from 0 to 45 years based on selected filters (Figure 2a).

- *What:* It uses the ages of all turbines of a municipality, which are crucial for planning inspections and maintenance, enhancing operational efficiency and safety.
- *Why:* This view gives a detailed overview of the ages of turbines in a selected area. It can be used to spot older and newer clusters of turbines.
- *How:* A bar chart that groups the number of turbines by their age in years is used.

- *Use:* Analysts can explore turbine lifecycle stages and spot maintenance needs. Operational efficiency can be assessed, upgrades or replacements planned, and investment decisions supported by analyzing turbine ages across regions and manufacturers.

Wind Production View: For a selected municipality, the electricity production from wind energy is visualized (Figure 2b).

- *What:* It shows the annual electricity production in gigawatt-hours (GWh) from 1977 to 2021 (**R2**), enabling interactive selection of time periods for in-depth research.
- *Why:* This view reveals regional wind energy trends, supporting strategic planning, policy-making, and investment decisions by comparing annual production changes.
- *How:* Bars represent yearly production volumes, with the height indicating the amount of electricity produced.
- *Use:* Analysts can explore the total production of selected municipalities, guiding towards more detailed inspection.

Market Share View: For the selected set of wind turbines, the market share is shown to support detailed analyses (**R4**, Figure 1d).

- *What:* It uses the counts of selected turbine manufacturers.
- *Why:* This view aims to compare manufacturers and spot market trends, helping stakeholders assess market dominance and strategic positioning regarding turbine quantity and capacity.
- *How:* The market share is illustrated with an interactive doughnut chart that depicts market shares using a categorical color map, facilitating quick industry comparisons and insights.
- *Use:* Next to supporting the detailed performance analysis with manufacturer information, for selected regions, analysts can explore manufacturer's market shares, and their specialization in onshore or offshore turbines.

Total Electricity Production View: A static chart gives contextual information on the development of the energy market (Figure 1e).

- *What:* It shows annual data of Denmark's energy market from 2000 to 2022 (**R4**), including various energy sources.
- *Why:* This view aims to compare energy sources and to spot trends like the shift from fossil to renewable energy.
- *How:* A stacked bar chart shows the energy mix per year.
- *Use:* The view gives important contextual information to a detailed analysis, highlighting the growing importance of wind energy and its impact on energy policy and investments.

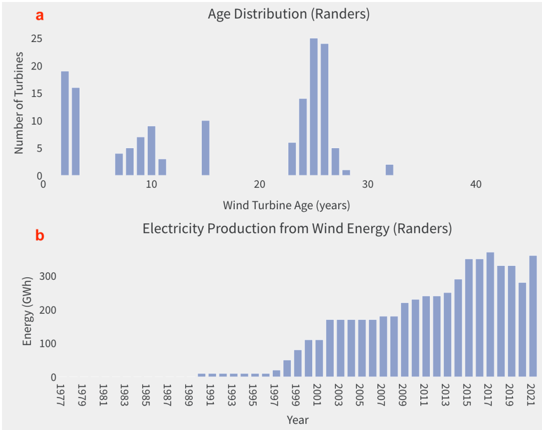

Figure 2: *Age distribution view (**a**) and wind electricity production view (**b**) for the municipality Randers.*

5. Discussion & Conclusion

To depict and support the transition from fossil to renewable energy sources, particularly focusing on the role of wind energy in Denmark, we developed the Danish Wind Power Analytics Tool (DWPAT) with industry experts and researchers. It includes features for visualizing wind turbine distribution, providing insights into their development over time, comparing turbine performance and size, and supporting detailed analysis through various visual representations. DWPAT supports complex filtering by various attributes like manufacturer and installation type, aiming to support informed decision-making in the energy sector by enabling a detailed exploration and comparison of wind turbine data.

Limitations. We have not yet conducted an extensive user study. However, the tool was specifically designed to meet the needs of domain experts, and the prototype was continuously evaluated and their valuable feedback was incorporated throughout the development process [JKKS20]. Another limitation is the static data, which only shows a realistic view of the historical wind power production. However, according to information from the Danish Energy Agency, the cessation of updates is attributed to a transition to a new live database, which is expected to become available. Lastly, comparisons on turbine level are currently only supported for two selected turbines. Comparing a larger set of turbines could yield further strategic insights for analysts.

Future Work. Next to set selections, our current prototype focuses mainly on wind turbine sizes and capacities. For some wind parks, the actual wind power production information is evenly distributed across its turbines. However, some wind parks provide detailed performance per turbine, which could be integrated into different views. Other potentially significant additions could include a temporal view of wind turbine count and the ability to filter the visualizations based on wind turbine age, dimensions, or capacity to help filter out non-relevant wind turbines. Our main future focus includes correlating wind turbine data with (live) weather data for a more comprehensive analysis of geospatial and temporal patterns, which could be beneficial to spot windy areas without wind turbines.

Despite its limitations, DWPAT represents a step towards giving a better understanding of the complex landscape of wind turbines in Denmark. We want to emphasize the general approach of our design and dashboard prototype, which is applicable to other regions with similar wind power data available.

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